UCRL-84028
PREPRINT

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This paper was prepared for submittal to
Applied Physics Letters

February 1980

Lawrence Livermore Laboratory

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ABSTRACT

Pump depletions of 70-75% have been demonstrated for a KrF laser-driven, methane gas-filled backward Raman amplifier and are in agreement with predictions of the Frantz-Nodvik saturated amplifier model. The associated counterpropagating Stokes laser intensity is measured to be $\gtrsim 3.5$ times that of the pump; the corresponding pulse compression ratio is ≈ 5.

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*Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore Laboratory under contract number W 7405-ENG-48.

Requirements on advanced laser drivers for inertial confinement fusion have been fairly well defined.[1] The requisite 1-10 Hz repetition rate is most readily achieved by gaseous media, although selected solid state emitters and excitation scenarios may be important in this context.[1,2] Use of the efficient rare gas halide lasers has recently been considered for this application employing the pulse-shortening techniques of backward wave Raman pulse compression[3] and pulse stacking[4] to achieve the necessary high intensities. Earlier related work on Raman pulse compression emphasized KrF laser-pumped, methane gas-filled backward amplifiers operating in the small signal[5] and moderately saturated regimes[6]. Here we present results under more heavily saturated conditions corresponding to pump depletions of 70-75% by the counterpropagating Stokes wave at 268 nm.[7] For this case, the Stokes laser intensity is determined to be $\gtrsim 3.5$ times greater than the pump intensity while the associated pulse compression ratio is measured to be ≈ 5. Additional investigations have been made at extraction efficiencies of 50% and 30% correlating to higher pulse compression ratios. All three experimental results stand in good semi-quantitative agreement with an analysis based on the Frantz-Nodvik saturated amplifier treatment.[8] Model verification is vital for characterizing the performance features of short-wavelength megajoule-class laser-fusion systems, utilizing this approach, that are currently contemplated for commercial power generation.[1]

The present investigation employs four uv-preionized KrF discharge gain media to produce a nominal 1 J of pump energy at 248 nm in a pulselength about 35 ns and a linewidth 0.15-0.20 cm^{-1} . Such relatively high spectral purity is necessary to minimize the forward-to-backward Raman gain ratio.[3] A master oscillator, using three intra-cavity etalons to achieve the narrow linewidth, produces a 20 ns-long, 1 mJ pulse that injection locks a similarly-sized (1/2 x 1 x 100 cm^3) gain medium equipped with unstable resonator optics to generate a 150 mJ output. Details on a basically identical approach have been reported.[9] A fraction of this energy is used, in turn, to injection lock a larger KrF discharge volume that also uses an unstable optical cavity and that has a gain region of 1 x 4 cm^2 cross section by 1 m length. This source delivers up to about 1 J laser energy when operated as an oscillator with a stable cavity (4% flat output coupler and 10 m maximum reflector at 248 nm). In practice, to reduce stressing the various components, the electrical excitation for this discharge is kept at reduced values corresponding to stable oscillator outputs 1/3 to 1/2 the maximum value. Finally. the 35-ns long injection-locked pulse is amplified by single passage through a second identical amplifier resulting in a total 248 nm line-narrowed pump energy about 1 J. The four KrF discharges use gas mixtures of 0.4% F_2, 10% Kr, with the balance He at total pressures 1-1.5 atm. A master trigger unit fires the devices with relative jitters among the discharges of less than a few ns.

Figure 1 illustrates the parceling out of the KrF pump laser intensity to a Stokes oscillator (that operates via stimulated forward Raman scattering), a backward Raman preamplifier, and a backward Raman amplifier. For the current investigations the three stainless steel cells, capped with 2 cm thick uv-grade quartz windows, were all operated at about 380 psi methane pressure. The 1.5 in. diameter cells had the following lengths in ns: oscillator - 10.3, preamplifier - 10.3, amplifier - 14.0. As seen in Fig. 1, the preamplifier and amplifier are each equipped with pump delay mirrors. The Raman cell interiors designated by solid circles denote the intersection of the leading edges for the pump and Stokes waves. For the preamplifier, which is operated under small-signal Raman gain conditions, the pump delay option permits passive time tailoring of the transmitted Stokes pulse. In general, a Stokes pulse with a slow rise time is desired for passage through the saturated amplifier to prevent formation of too-steep a leading edge that, too-rapidly, reaches the production threshold for the second Stokes wave in the backward direction. Note that this parasitic process generated by the back-traveling first Stokes wave involves forward Raman scattering and, therefore, can have a relatively high cross section.[3] The pair of pump delay mirrors associated with the saturated amplifier serve primarily as a convenience to fine tune the intersection location for the pump and Stokes pulses. Mirrors with partially transmitting dielectric coatings, as indicated in Fig. 1. allow for recording the input/output beams for the two amplifiers. The pump and Stokes pulses transmitted by these mirrors were viewed by photodiodes equipped with apertures a few mm in diameter that were positioned to correspond with spatially smooth sections of the pump beams.

Shown in Fig. 2 are representative waveforms for the pump and Stokes pulses exiting the saturated amplifier. The traces are recorded with S20-sensitive photodiodes, having response times $\lesssim 1$ ns, and Tektronix 519 oscilloscopes. In Fig. 2a the effect of a counterpropagating Stokes wave on reducing the transmitted pump intensity is clearly evident. Electronic integration of these signals indicates that the photon extraction efficiency is 70-75%, while the energy extraction efficiency is lower by a factor 248/268 = 0.93. Since the Stokes pulse is created in the local oscillator by stimulated forward Raman scattering, the back-traveling 268 nm wave begins with a relatively long duration, roughly equal to that of the 248 nm pump beam. Consequently, because of the relatively short lengths of the Raman amplifiers used in this study, all parts of the counterpropagating Stokes pulse do not sweep through the pump beam in a methane background. Therefore, final portions of the Stokes pulse see little, if any, Raman gain. For the selected pump beam optical delay, the Stokes pulse exiting the small-signal preamplifier has a relatively slow risetime compared to cases for which the pump/Stokes pulse-edge intersections are positioned closer to the oscillator output. A detailed experimental study of pulse shape effects on saturated amplifier performance will not be part of this communication. However, straightforward computer modeling of pulse propagation effects, as described in what follows, underscores the utility of a slowly-rising backward first Stokes pulse in suppressing the onset of second Stokes generation and thereby maximizing the energy extraction from the pump beam.[8] Furthermore, passive pulse-shaping techniques, as used in the present study or supplemented by electrooptic techniques, can help produce laser temporal shapes that are considered optimal for target irradiation in inertial confinement fusion studies.[1]

The Stokes pulse emerging from the saturated backward Raman amplifier is depicted in Fig. 2b. It has a pulsewidth about 7 ns (FWHM), corresponding to a pulse compression ratio of five with reference to the 35 ns-long pump pulse. At the operating photon extraction efficiency level of 70-75%, the laser intensity enhancement of the counterpropagating Stokes wave is a factor $\gtrsim$3.5 with respect to the pump pulse. Operation below the second Stokes limit was confirmed by the presence of signals at the 292 nm second Stokes wavelength which were a few percent of the first Stokes signal strength. Thus, in this work, we have substantially shortened a relatively long Stokes oscillator pulse by the combined effects of: (i) low trailing-edge Raman gain in the relatively short methane amplifiers, and (ii) gain steepening in the saturated amplifier. For the present investigation, we merely require that the resultant Stokes pulsewidth be less than the saturated amplifier length. For this condition, the behavior of the trailing part of the Stokes pulse is not critical to our evaluation of the Raman pulse compression technique. If necessary, the trailing signal can be eliminated with standard electrooptic techniques. Data were also obtained at the second Stokes limit for photon extraction efficiencies of 50% and 30% corresponding to pulse compression ratios of about 10 and 25 respectively. In the latter case, about 35 mJ of first Stokes energy was obtained in a pulsewidth ≈1.5 ns.

The experimental results were compared against the predictions of a computerized Frantz-Nodvik saturated amplifier model characterizing Raman pulse compressors.[3,8] The main physics assumptions in this analysis include: (i) smooth plane waves, (ii) slowly varying amplitude approximation, (iii) exact resonance condition, i.e., $\nu_S = \nu_P - \nu_R$ where the labels are S = Stokes, P = pump, and R = Raman, and (iv) steady state scattering in which molecular transients are neglected. It also assumes that the length of the cell (L) and the timing of the pulses are close to the ideal where $L = 1/2\, ct_p$ and the Stokes pulselength is short compared to the pump pulselength (t_p). This condition is barely satisfied for the low compression results. Computer solutions of the propagation equations for the Stokes and pump waves were obtained under these conditions. Representative results are shown in Fig. 3 for which the photon extraction efficiency, at the second Stokes production limit, is plotted as a function of the parameter $R\kappa/G_f$ where R = forward-to-backward Raman gain ratio, κ = ratio of pump pulselength to exiting Stokes pulsewidth, and G_f = second Stokes gain. For the present investigation the R value, which is determined mainly by the scatterer linewidth at the operating methane pressure (380 psi) and the linewidth of the 248 nm pump[3], lies in the range 1.5 - 1.7. G_f is set equal to 20 corresponding to a nominal superfluorescence limit above which the second Stokes wave is readily produced. The data, as typified by Figs. 2a and b, permit for determination of the photon extraction efficiencies and $R\kappa/G_f$ values for the three distinct cases studied. The experimental results, along with their associated uncertainties, are plotted as boxes in Fig. 3. Fairly good agreement exists with the model calculations and, in particular, for the predictions that consider a positively-skewed Gaussian Stokes pulse incident on the saturated amplifier to characterize the data at the 50% and 30% photon extraction efficiencies. This representation is appropriate since no pump beam optical delay was used for the Raman preamplifier resulting in forward-leaning Stokes input pulses to the Raman amplifier. On the other hand, the measured extraction efficiency of 70 - 75% for the lowest compression case (which utilized the delay) appears to be somewhat less than the simulations indicate. Note that for this case, a more-appropriate Stokes input pulseshape is the negatively-skewed Gaussian. Most probably, this discrepancy is due to the non-plane-wave nature of the pulses used in the experiments, the lack of exact alignment between the Stokes and pump beams in the saturated amplifier. and the limitations of the modeling due to the finite amplifier cell length. Future experimental studies will evaluate the attributes of slower rising Stokes pulses by detailed modeling of amplifier output waveforms for well-characterized input pulse shapes.

The apparatus used in these investigations serves as the front end for an installation designated as RAPIER (Raman Amplifier Pumped by Intensified Excimer Radiation), which currently features an electron-beam-pumped, 35 J KrF gain medium.[10] Employing this facility, future reports will deal with Raman pulse compression experiments that evaluate larger-scale backward Raman amplifier performance. Specifically. assessments will be made at lower methane densities and larger Fresnel numbers. Operation under the latter condition will more critically test propagation behavior for large apertures where diffraction and interference effects are more representative of sizable target irradiation devices.

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Figure Captions

Fig. 1 Diagram of the experimental arrangement used in the backward wave Raman scattering studies. The total KrF pump laser intensity (solid line) is divided and directed to three methane-filled Raman cells which serve (bottom to top) as the Stokes oscillator (using stimulated forward Raman scattering to generate the 268 nm pulse shown as a broken line); backward Raman preamplifier, and amplifier. The two regions designated with solid circles indicate the intersection of the leading edges for both the pump and Stokes waves. Omitted for clarity are various focusing lenses and collimating telescopes.

Fig. 2 Photodiode traces of: (a) KrF pump laser and (b) 268 nm Stokes pulses exiting opposite ends of the methane-filled, backward Raman amplifier. In (a) the larger signal is recorded without the propagation of the back-traveling Stokes pulse; the smaller response with the passage of the Stokes wave. For each of these conditions, two traces are recorded in (a) to characterize the reproducibility of the data; in (b) a clarifying smooth line is drawn through the output Stokes pulse shapes. Electrical integration of the signals in (a) shows that the photon extraction efficiency is 70-75%. The output Stokes intensity is $\gtrsim 3.5$ times greater than the input pump intensity; the pulse compression ratio is ≈ 5.

Fig. 3 Photon extraction efficiency for a backward Raman methane amplifier as a function of the parameter $R\kappa/G_f$ (see text) at the generation limit for the second Stokes wave. Computations for three different input Stokes temporal pulseshapes are shown (solid lines) along with the experimental results and their associated uncertainties (boxes).

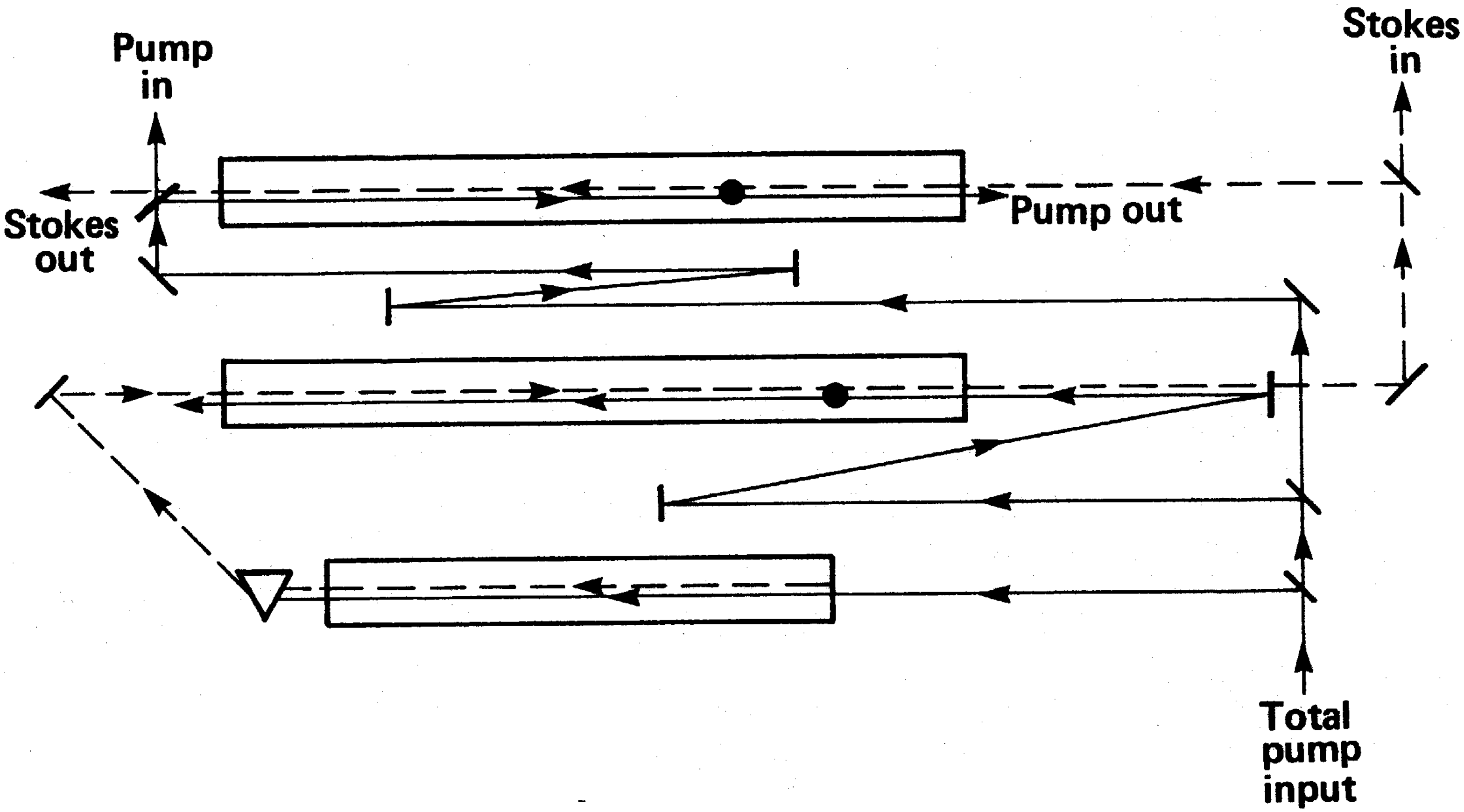


Fig. 1

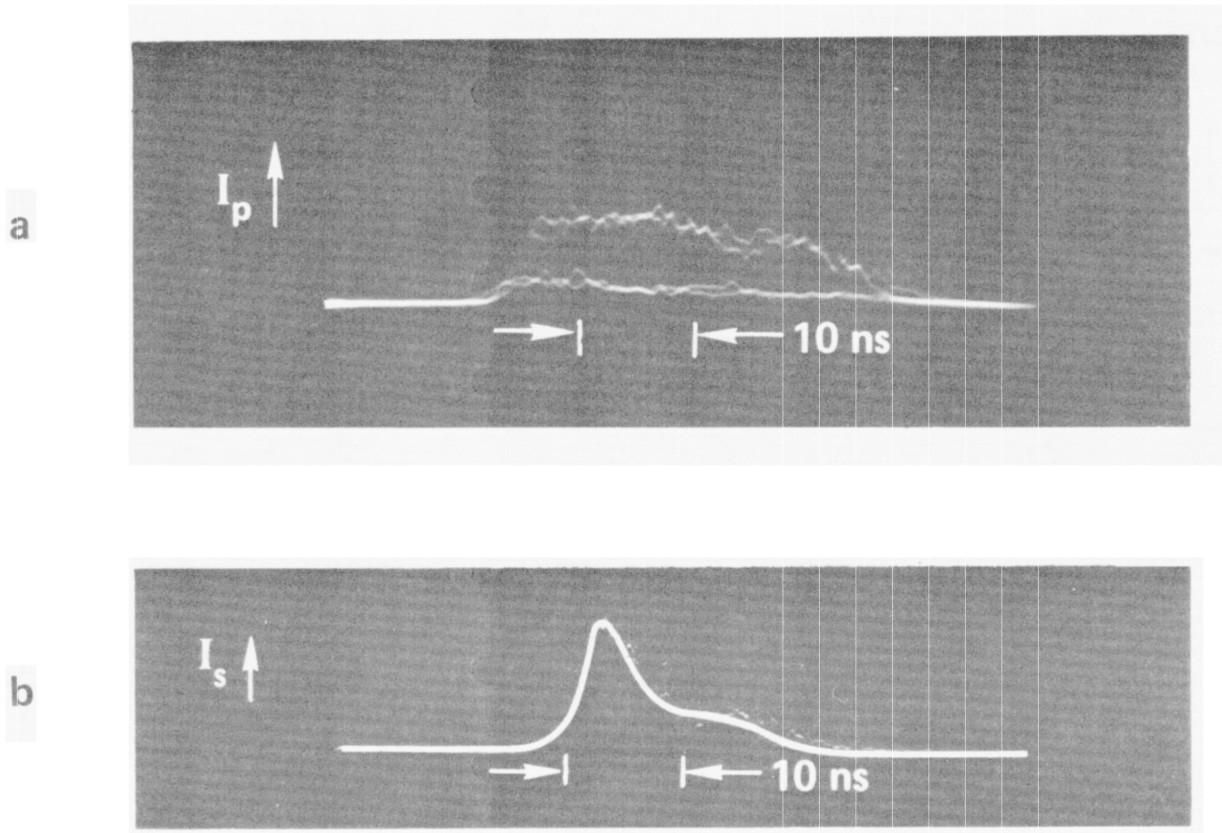
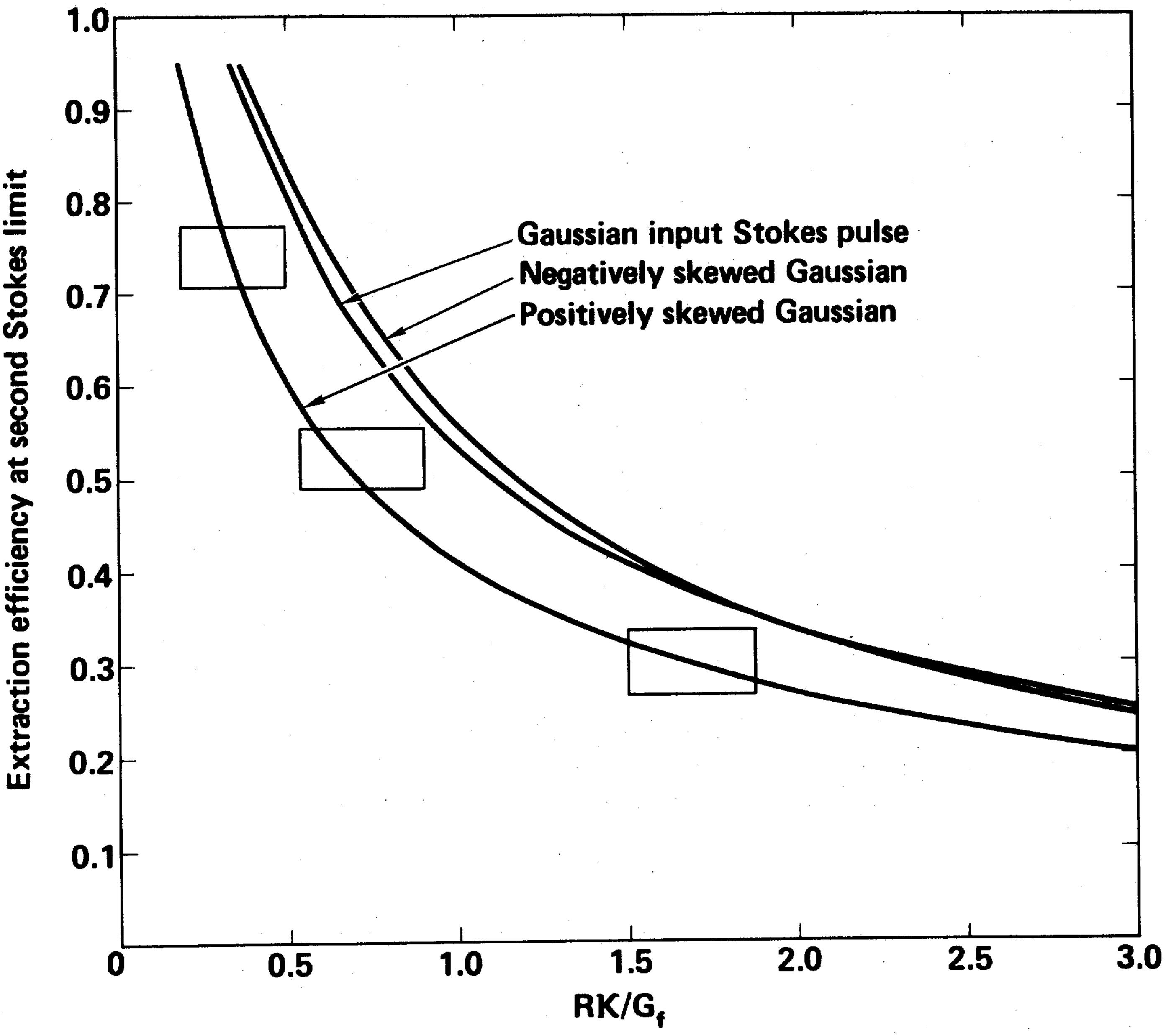


Fig. 2



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Extraction efficiency at second Stokes limit
Gaussian input Stokes pulse
Negatively skewed Gaussian
Positively skewed Gaussian
0
0.5
1.0
1.5
2.0
2.5
3.0
RK/G$_f$

Fig. 3